PCT WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : F16K 27/00	A1	(11) International Publication Number: WO 99/24744 (43) International Publication Date: 20 May 1999 (20.05.99)

(21) International Application Number: PCT/US98/24072

(22) International Filing Date: 12 November 1998 (12.11.98)

(30) Priority Data:

60/065,132	12 November 1997 (12.11.97)	US
60/077,945	13 March 1998 (13.03.98)	US

(71) Applicant: CALIFORNIA INSTITUTE OF TECHNOLOGY [US/US]; 1200 East California Boulevard, Pasadena, CA 91125 (US).

(72) Inventors: TAI, Yu-Chong; 369 S. Grand Oaks, Pasadena, CA 91107 (US). YANG, Xing; 136-93 E.E. Caltech, Pasadena, CA 91125 (US). GROSJEAN, Charles; 131-93 E.E. Caltech, Pasadena, CA 91125 (US). WANG, Xuan-Qi; 3400 Greenfield Avenue #7, Los Angeles, CA 90034 (US).

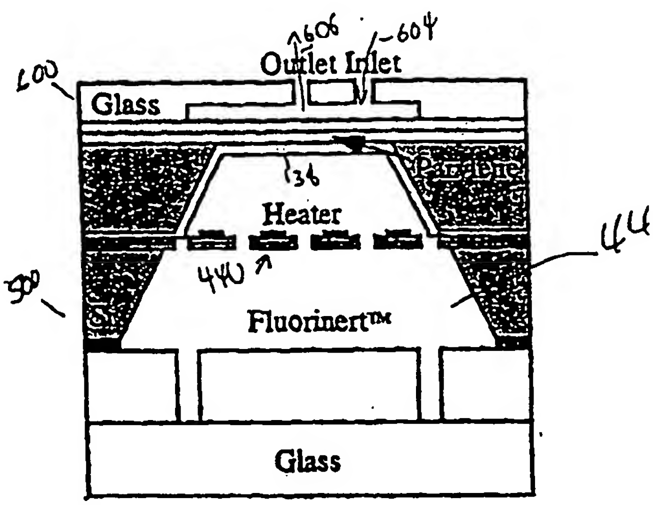
(74) Agent: HARRIS, Scott, C.; Fish & Richardson P.C., Suite 1400, 4225 Executive Square, La Jolla, CA 92037 (US).

(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published

With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: MICROMACHINED PARYLENE MEMBRANE VALVE AND PUMP



Cross-sectional View of the Normally Open Valve

(57) Abstract

A micromachined fluid handling device (600) includes a valve (138) made of reinforced parylene. A heater (440) heats a fluid to expand a thermopneumatic fluid (442). The heater (440) is formed on unsupported silicon nitride to provide a reduction in power.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece			TR	Turkey
BG	Bulgaria	HU	Hungary	ML	Mali	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MN	Mongolia	UA	Ukraine
BR	Brazil	IL	Israel	MR	Mauritania	UG	Uganda
BY	Belarus	IS	Iceland	MW	Malawi	US	United States of America
CA	Canada	IT	Italy	MX	Mexico	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NE	Niger	VN	Viet Nam
CG	Congo	KE	Kenya	NL	Netherlands	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NO	Norway	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	NZ	New Zealand		
CM	Cameroon			PL	Poland		
CN	China	KR	Republic of Korea	PT	Portugal		
CU	Cuba	KZ	Kazakstan	RO	Romania		
CZ	Czech Republic	LC	Saint Lucia	RU	Russian Federation		
DE	Germany	LI	Liechtenstein	SD	Sudan		
DK	Denmark	LK	Sri Lanka	SE	Sweden		
EE	Estonia	LR	Liberia	SG	Singapore		

MICROMACHINED PARYLENE MEMBRANE VALVE AND PUMP

Cross Reference To Related Applications

This application claims the benefit of the U.S. Provisional Application No. 60/065,132, filed on November 12, 1997, and 60/077,945 filed March 13, 1998, both of which are incorporated herein by reference.

Statement as to Federally Sponsored Research

The U.S. Government may have certain rights in this invention pursuant to Grant No. N66001-96-C-8632 awarded by the U.S. Navy.

Background

Micromachining is the science of forming various features on silicon structures. These features can be formed to relatively small sizes. Strength of the eventual features is a very important issue.

Thermopneumatic actuation can allow micro-sized fluid handling devices.

Summary

The present disclosure describes using Parylene membranes along with micromachining of structure form various features. Another embodiment uses a composite of Parylene and silicone rubber to obtain certain advantages of each of the materials.

One embodiment teaches using robust Parylene membranes, formed using silicon micromachining technology, to form several fluid handling devices. These include a thermopneumatic actuator, valve, and pump, all of which operate using a heater in a thermopneumatic liquid. These devices have small size, high performance, low cost, and low power.

Another embodiment teaches using a composite of Parylene and silicone rubber.

Brief Description of the Drawings

These and other aspects of the invention will now be described with reference to the attached drawings, in which:

Figures 1A - 1F show stages of forming the Parylene membrane;

Figure 2 shows a cross section of the heater;

Figure 3 shows a top view of the heater;

Figures 4A - 4E show steps of forming the heater;

Figure 5 shows a cross section of a thermopneumatic actuator;

Figure 6 shows a cross section of a normally open valve;

Figure 7 shows a peristaltic pump; and

Figures 8A - 8G show steps of forming a high density membrane;

Figures 9A - 9F show forming a composite silicone/parylene membrane;

Figure 10 shows a valve seat in cross section;

Figure 11 shows the valve seat from above;

Figures 12A -12C shows forming the valve seat;and

Figure 13 shows a cross sectional view of the valve.

Description of the Preferred Embodiments

The present embodiment describes formation of a Parylene membrane. Parylene is available from Specialty Coating Systems, Inc., 5707 West Minnesota Street, Indianapolis, IN 46241. The basic process is shown in FIGs. 1A-1F.

First, a silicon substrate 100 is heated at 1050°C to form a 2 μm thick silicon dioxide layer of native oxide 102 on its front surface 101. The silicon dioxide layer 102 is formed on the front surface 101. The rear surface 104 is also formed with a silicon dioxide layer 106. The rear layer 106 is patterned and etched using buffered hydrofluoric acid ("BHF") to open windows 104. The wafer front side, and the remaining areas 106, can be covered with photoresist during this time.

FIG. 1B shows a window 110 being opened in the silicon back side 104, between the silicon dioxide layers 106, using anisotropic etching. The preferred anisotropic etchant is KOH. This etches the silicon substrate until the thinned silicon portion 112 is between 20 and 100 μm thick.

At this time, the silicon dioxide layer 102 is removed from the front layer. This is done by using buffered hydrofluoric ("BHF") acid. A 2 μm thick layer 120 of Parylene is deposited over the entire wafer front and back. This includes a deposition on the front surface 122 and a deposition 124 in the window area 110.

In FIG. 1D, the back side Parylene 124 is removed using an oxygen plasma. This is followed by removing the thinned silicon 112 layer using BRF_3, leaving a free-standing Parylene layer 122.

FIG. 1F shows a second Parylene deposition process which again deposits the material over the entire surface of both sides. The second Parylene layer results in a top layer 130 and a bottom layer 132. Notably, the bottom layer 132 results in significant edge membrane strengthening.

The result is that a strengthened-edge Parylene membrane which is unsupported by silicon, is formed between the edge portions 134 and 136.

Thermopneumatic actuation uses a heater to heat up a thermopneumatic liqud, and cause it to expand and contract. It

is desirable to have a thermally efficient heater to minimize the amount of power necessary to heat the liquid.

Figures 2 and 3 show a thermally efficient heater as used according to the preferred embodiment. Figure 2 shows a cross sectional view of the heater. A free-standing silicon nitride membrane is formed using a technique described in further detail herein. Gold heaters 200 are formed on the free-standing silicon nitride substrate. Silicon nitride has a very low thermal conductivity, and forms a very thin membrane, e.g. 0.5 μm thick, less preferably less than 1μm thick, or less than 2μm thick. The thin membrane is preferably unsupported by any higher thermal conductivity material. This yields a very high thermal resistance which minimizes undesired heat loss.

FIG. 2 shows the cross sectional view of the heater, while FIG. 3 shows a drawing of the fabricated heater looking from the top. The holes in the membrane help to equalize the pressure on the front and back of the membrane. It has been found through experiments with only 52.2 milliwatts of power, the surface of the gold heater can reach 200°C. The heater material is preferably formed in a zig-zag pattern as shown.

FIGs. 4A-4E show the fabrication process of the heater. First, a layer of thermal conductivity material, preferably a ½ μm thick, low stress LPCVD silicon nitride 400 is deposited on the silicon substrate 402. The silicon nitride is deposited at

850°C with a $SiH_2Cl_2:NH_3$ gas flow ratio of 4 to 1. Windows 404 are opened on the back side of the wafer. This can be done using dry etching with the desired portions being covered with photoresist.

FIG. 4B shows an anisotropic etching step in which the wafers are etched in an anisotropic etchant such as KOH. This leaves a thin silicon area 410 which is between 20-100 μm thick.

FIG. 4C shows the gold heater deposition, in which a layer of resistive material, e.g., Cr/Au, is thermally evaporated on the front side of the wafers. The material is patterned to define the resistive pattern that is desired. Preferably the zig-zag shaped resistive pattern shown in FIG. 3 is used.

An array of holes such as 430 is then etched into the silicon nitride layer using RIE as shown in FIG. 4D.

Finally, the wafer is put back into the anisotropic solution of KOH to remove the thin silicon area 410, leaving a free-standing silicon nitride element shown in Fig. 4E.

FIG. 5 shows the overall view of the thermopneumatic actuator assembled using the components above. The thermopneumatic actuator is made by assembling a Parylene membrane chip 150 as shown in FIG. 1F on top of the heater chip 210 shown in FIG. 2.

The cavity formed between the chips is filled with a thermopneumatic liquid 502 which is preferably an expansive

liquid. The cavity is also sealed by a stacking plate. A bottom layer of glass 510 is formed to seal the device.

This device can be used with various liquids including air, 3M fluorinert PF5060, in either 50% solution or full solution, alcohol, water, distilled water, or PF5070. The PF5060 is believed to give the best performance. This forms the actuator, which can be used with various other structure.

FIG. 6 shows the actuator device 500 being topped with a valve device 600. The Parylene membrane portion 138 forms the actuator for the valve device. The valve shown in FIG. 6 is normally opened, and fluid can pass from its inlet 604 to its outlet 606. When the heater 440 is actuated, the fluid in cavity 442 expands, causing the Parylene membrane 138 to bubble up and block the communication between the inlet 604 and the outlet 606.

FIG. 7 shows a thermopneumatic peristaltic pump formed using similar technology. This pump is made by putting three or more thermopneumatic actuators in line on a single substrate inside a housing 701. The overall device is shown in FIG. 7. A glass inlet/outlet die 704 is formed and fluid enters through the inlet 700 and exits through the outlet 702.

Layer 710 is a silicone membrane with a fluid impermeable layer - preferably a Parylene vapor barrier. Each Parylene vapor barrier forms an actuator, which selectively extends all the way up to the bottom surface 706 of the glass inlet/outlet die when

heated by an associated heater 722. The Parylene membranes 712, 714, 716 are actuated by respective heaters 722, 724, 726 in the layer 720. For instance, the heater 722 is heated to actuate the liquid close to heater 722, to expand the Parylene membrane 712. Separators between the adjacent cavities are formed by the silicon areas 713.

In operation, the actuators are deflected sequentially from left to right, with a small overlap period. This effectively pumps the liquid from the inlet to the outlet. First, the heater 722 is actuated, and during its deactuation, the heater 724 is actuated. During that deactuation, the heater 726 is actuated. This pumps the liquid from inlet to outlet.

Both Parylene and Parylene/silicon membranes can be used for the actuator. Parylene has been shown to be an effective vapor barrier for 3M fluorinert liquids.

The heaters are fabricated in a similar manner to that described above, except that three or more heaters are fabricated on the same substrate. The heaters and the membranes are formed with similar spacing to form a single peristaltic pump.

The fabrication process is similar to that described above. In addition, a layer of silicone rubber can be added to the Parylene to aid in robustness.

In addition, higher density and lower dead volume can be carried out using a special process with a polysilicon

sacrificial layer. This can be used to achieve closer membrane spacing and better surface coverage than the other membranes formed by simple anisotropic etching. FIGs. 8A - 8G shows this alternative embodiment. This, however, has the additional complexity of requiring etching a polysilicon spacer/sacrificial layer after the Parylene membranes are formed.

FIG. 8A shows both thermal oxide layer 800 and a silicon nitride layer 804. The back side layers are patterned as described previously to open windows 809.

In FIG. 8B, cavities 810 are opened in the silicon 802 using KOH. The oxide layer 800 is also stripped from the back side of the openings to leave free-standing SiN portions 814.

Step 8C shows further passivating the walls of the windows with a thermal oxide 820. The silicon substrate needs to be completely passivated in order to obtain high selectivity when using bromium trifluoride. The free-standing S_1N membranes 814 are also covered with thermal oxide 820 covering all of the other surfaces.

In step 8D, polysilicon 830 is grown on the top and bottom surfaces using a positive photoresist. This pattern forms the membrane areas.

FIG. 8E shows Parylene layer 840 being deposited over the front surface to form the final membrane material. The silicon nitride membranes are removed using plasma, and polysilicon is

removed and undercut with bromium trifluoride as shown in FIG. 8F. This leaves closely packed Parylene membranes. FIG. 8G shows an additional layer 860 of silicon rubber being deposited on top of the overall substrate as a strengthening layer.

Silicone is an interesting material for the valves. Silicone rubber has a low modulus, approximately 1 MPa, good compatibility with IC processes and high elongation. The sealing process of silicone rubber is quite excellent. Silicone rubber can seal against rough surfaces, and still have virtually zero flow rate when closed. However, a main issue with silicone rubber is that it is permeable to and absorbs much of the liquids that have otherwise been used for thermopneumatic actuation.

The embodiment as described herein uses a composite membrane technology. The membrane is in contact with liquid in a micromachined cavity within a silicon substrate. An impermeable film is used between the liquid and silicone rubber in order to prevent the liquid from leaking out. This embodiment uses Parylene as the impermeable film. Parylene also has a very low modulus, as well as low permeability to the thermopneumatic actuation fluids including fluorinert, water, isopropyl alcohol, and the like. The Parylene layer is connected to an elastomeric substance, preferably silicone rubber.

This embodiment uses a heater as shown in Figures 2 and 3, sitting on a relatively thin free-standing silicon nitride

membrane. The membrane is preferably less than 0.5 μm in thickness, and silicon nitride also has a very small thermal conductivity. This reduces the heat loss and hence improves the power efficiency.

Another embodiment is disclosed herein includes a novel valve seat. This novel valve seat uses concentric grooves etched into the substrate around the hole. The grooves reduce the chance of the particles sticking near the inlet and outlet. They also form a redundant seal and reduce the leak possibility of the valve when closed.

FIGs. 9A-9F represent the composite silicone/Parylene membrane fabrication process. FIG. 9A shows first forming a 2-μm thick silicon oxide via thermal oxidation on the wafer surface. This layer is used as a barrier to etching. Etching windows are opened by patterning that silicon oxide layer using photolithography. Buffered hydrofluoric acid, for example, can be used to selectively remove the etch barrier.

The wafers are then immersed into an anisotropic silicon etchant such as KOH. This etches the silicon wafer from both the front and back side until approximately a 20-μm thick silicon membrane 900 remains in the middle of the wafer.

At this time, the remaining silicon oxide 902 is removed using BHF. Step 9B illustrates growing isolation layers, preferably silicon nitride layers, approximately 0.5 μm thick, on

both surfaces of the substrate using low pressure chemical vapor deposition. The silicon nitride layer 912 on the back surface is removed using CF_4/O_2 plasma etching. This leaves only the silicon nitride 910 on the front surface.

FIG. 9C illustrates replacing the wafers into a KOH solution to etch away the remaining 20-μm thick silicon layer in the middle of the wafer 900. This forms a free-standing portion 920 of the silicon nitride membrane 910. FIG. 9D illustrates forming a 2-μm thick layer of thermopneumatic-impermeable material, preferably Parylene, 930, on the top of the free-standing layer, but extending beyond the edges of the free-standing layer. This can be formed, for example, using a vapor deposition process. Again, the photolithography process is used to pattern the Parylene layer, followed by selective removal using oxygen plasma etching.

The remainder of the well 904 is then filled with elastomeric material, preferably silicone rubber on the front side. The silicon nitride 910 can then be removed from the back side using CF_4/O_2 plasma etching. Finally, another layer 950 of 2-micron thick Parylene is deposited on the back side of the wafer to replace the removed silicon nitride layer.

This forms a composite silicon/Parylene membrane.

A valve seat embodiment is described with reference to FIGs. 10, and 12A-12C. This special valve seat has concentric grooves

instead of simple holes for inlet and outlet. The grooves reduce the chance of particles becoming obstructions near the inlet and outlet, by effectively serving as particle traps. FIG. 10 in fact shows a sample particle 1004 trapped in one of the grooves 1000. Another particle 1006 is shown out of a groove. However, since silicone rubber is elastomeric, it can completely wrap around the particle 1006, as shown. The grooves form a reliable and redundant seal. When closed, the grooves reduce the leak rate between the inlet 1010 and the outlet 1020.

As discussed above, the system preferably includes a number of sets of concentric grooves 1000, 1001, and 1002, concentrically surrounding the inlet 1010. Figure 11 shows 17 sets of grooves, but any number of sets of grooves between 2 sets of grooves and 30 sets of grooves is within the preferred embodiment. The grooves could alternately be formed surrounding the outlet 1020, if the outlet is being sealed. The membrane 1030 is formed of an elastomer, e.g., silicone rubber.

The valve seat fabrication process is illustrated in FIG. 12. First, a 2-micron thick silicon dioxide 1204 is thermally grown on the wafer at 1050°C. As in previous embodiments, the silicon dioxide layer on the wafer backside is patterned using photolithography and KOH and then etched using buffered hydrofluoric acid to open window 1200 in the wafer. Preferably,

the etching continues until approximately a 15 μm silicon area is left at area 1206.

FIG. 12B illustrates etching the grooves 1600, 1602 into the top surface 1210 of the substrate using reactive ion etching. Finally, the silicon dioxide layer 1204 is totally removed as shown in FIG. 12C using BHF.

The fabricated valve seat is shown in FIG. 11. In this embodiment, the groove portions of the valve are formed in concentric squares, although any shape could be used.

FIG. 13 shows a cross section of the final valve. The system includes the heater as shown in FIGs. 2-4, formed in a cavity 1300 that is filled with thermopneumatic fluid, e.g, fluorinert. The silicone rubber/Parylene membrane chip portion 1310 is of the type described above. The valve seat chip portion 1320 uses the type of valve seat shown in FIGs. 11 and 12.

Each of the chips can be more or less the same thickness, or of different thicknesses. If the chips 1310 and 1302 are similar thicknesses, then the heater 200 will be substantially centered in the cavity 1300, as is preferred.

In operation, when no power is applied, the valve is open. When electrical power is applied to the gold resistors 200, the fluorinert expands. This raises the pressure inside the cavity 1300 which outwardly deflects the flexible silicone rubber/Parylene membrane 1310. This presses that membrane

against the valve seat thereby shutting off communication between the inlet and the outlet.

Although only a few embodiments have been described in detail above, other embodiments are contemplated and are intended to be encompassed within the following claims. In addition, other modifications are contemplated and are also intended to be covered.

For instance, other elastomeric materials and fluid impermeable materials could be used in place of the preferred silicone rubber and Parylene. Also, another low thermal material could be used in place of the silicon nitride. Certain ones of the semiconductor processing steps could be omitted or changed.

All such modifications are intended to be encompassed within the claims.

What is claimed is:

1. A micromachined fluid handling valve, adapted to be in contact with a selectively heated thermopneumatic liquid, said valve having a first part that makes the device impermeable to said thermopnematic fluid, and which is formed of a Parylene, and a second part, formed in a way that causes it to open and close based on the selective heating of the thermopneumatic fluid, and which is formed of an elastomeric material.

2. A parylene membrane, comprising:

a silicon substrate, formed to have first and second sidewalls and an open space between said first and second sidewalls;

a first layer of Parylene membrane, extending over said open space; and

a second layer of Parylene membrane, extending along said sidewalls, under said first layer of Parylene to thereby form strengthened edge portions at locations where said sidewalls meet said first layer of Parylene.

3. A device as in claim 2 wherein a center portion of said parylene membrane is unsupported by any portion of said silicon substrate.

4. A method of forming a parylene membrane, comprising:

forming a window on a rear side of a silicon substrate by etching to form a thinned silicon portion between said rear side of said silicon substrate and a front side of said silicon substrate;

forming a parylene membrane layer over said thinned silicon portion; and

removing said thinned silicon portion to thereby form a freestanding layer of parylene between unthinned edge end portions of the silicon substrate.

5. A method as in claim 4 further comprising forming a reenforcing parylene layer on a backside of said free standing parylene layer and on said window portion to strengthen edges of said parylene membrane layer.

6. A micromachined thermally-efficient heater, comprising:

a supporting sidewall foremd of a silicon material;

a thin material of a thickness less than 2 μm thick, having a low thermal conductivity, extending between said sidewalls, and having an unsupported portion which is unsupported by any material with a higher thermal conductivity; and

a heater, formed on said unsupported portion of said low thermal conductivity material.

7. A heater as in claim 6 wherein said low thermal conductivity material is silicon nitride.

8. A heater as in claim 7 further comprising a plurality of holes in said silicon nitride material to allow equalization of pressure between front and back of the silicon nitride layer.

9. A heater as in claim 6 wherein said low thermal conductivity material is ½ μm thick.

10. A system as in claim 7 wherein said silicon nitride layer is ½ μm thick.

11. A system as claim 7 wherein said silicon nitride layer is less then 1 μm thick.

12. A systems as in claim 6 wherein said low thermal conductivity material is less than ½ μm thick.

13. A system as in claim 12 wherein said heater layer is formed of gold.

14. A system as in claim 13 wherein said heater material is formed in a zigzag pattern on the surface, and further comprising a plurality of holes in the lower thermal conductivity material to allow equalization of pressure on opposite sides of the low thermal conductivity material.

15. A method of forming a high efficiency micromachined heater, comprising:

obtaining a silicon substrate;

forming a window in the silicon substrate which leaves a thinned silicon portion extending between two supporting sidewalls;

forming a thin layer of material of low thermal conductivity material on said thinned silicon portion;

forming a layer of resistive material over said low thermal conductivity material;

patterning said resistive material to form a desired resistive pattern; and

removing said thinned silicon area to leave a free-standing portion of said low thermal conductivity material extending between said silicon sidewalls with said layer of resistive material thereon.

16. A method as in claim 15 wherein said thinned silicon area is between 20 and 100 μm thick.

17. A method as in claim 15, wherein said material of low thermal conductivity is less than 2 μm thick.

18. A method as in claim 17 wherein said material of low thermal conductivity is silicon nitride.

19. A method as in claim 18 wherein said material of low thermal conductivity is ½ μm thick.

20. A method as in claim 15 further comprising forming holes in the material of low thermal conductivity to allow equalization of pressure between the front and rear sides of the material.

21. A method as in claim 20 wherein said low thermal conductivity material is less than 1 μm thick.

22. A thermopneumatic actuator comprising:

a base;

a cavity formed from sidewalls of micromachined silicon;

a membrane, formed from a silicon substrate, formed to have first and second sidewalls and an open space between said first and second sidewalls, a first layer of membrane material extending over said open space; and a second layer of membrane material, extending along said sidewalls, under said first layer of membrane material to thereby form strengthened edge portions at locations where said sidewalls meet said first layer of membrane material; and

a free standing heater, located in said cavity and formed from a thinned material which has low thermal conductivity , and operating to selectively heat thermopneumatic liquid in said cavity to expand the membrane or cool the thermopneumatic liquid to contract the membrane.

23. An actuator as in claim 22, wherein said heater comprises:

a supporting sidewall formed of a silicon material;

a thin material of a thickness less than 2 μm thick, having a low thermal conductivity, extending between said sidewalls, and having an unsupported portion which is unsupported by any material with a higher thermal conductivity; and

a heater, formed on said unsupported portion of said low thermal conductivity material.

24. An actuator as in claim 23, wherien said thin material is less than 1 μm in thickness.

25. An actuator as in claim 23, wherein said thin material is SiN.

26. An actuator as in claim 23, wherein said membrane is formed of a material including Parylene.

27. An actuator as in claim 26, wherein said membrane is formed of a material including a first portion which is resistant against infiltration by said thermopneumatic fluid, and a second portion, which is not in contact with said themopneumatic fluid, and which includes an elastomeric sealing portion.

28. An actuator as in claim 27, wherein said elastomeric sealing portion is silicone rubber.

29. An actuator as in claim 23, wherein said resistive material is formed in a zig zag portion, and said low thermal conductivity material includes holes therein adjacent to said zig zag portion.

30. An actuator as in claim 29, wherein said resistive material is formed of gold.

31. A device as in claim 21 wherein said liquid is 3M Flourinert.

32. A device as in claim 21 further comprising a valve device, covering the actuator device, and being normally open between inlet and outlet, and closing between inlet and outlet when said heater is actuated, to expand the liquid thereby expanding said membrane.

33. A device as in claim 21 wherein said valve also includes a layer of elastomeric material.

34. A device as in claim 21 further comprising a plurality of additional heaters, a plurality of additional membranes, an inlet area and an outlet area, said device operating as a pump.

35. A micromachined valve device, comprising:

a thermopneumatic actuator that has:

a base;

a cavity formed from sidewalls of micromachined silicon;

a membrane, formed from a silicon substrate, formed to have first and second sidewalls and an open space between said first and second sidewalls, a first layer of membrane material extending over said open space; and a second layer of membrane material, extending along said sidewalls, under said first layer of membrane material to thereby form strengthened edge portions at locations where said sidewalls meet said first layer of membrane material; and

a free standing heater, located in said cavity and formed from a thin material which has low thermal conductivity, and operating to selectively heat thermopneumatic liquid in said cavity to expand the membrane or cool the thermopneumatic liquid to contract the membrane; and

an inlet and outlet area, having an inlet adjacent said outlet with said thermopneumatic actuator therebetween, and operating to actuate said heater to expand said fluid to close fluid communication in said valve and to prevent fluid communication between said inlet and outlet.

36. An actuator as in claim 35, wherein said heater comprises:

a supporting sidewall formed of a silicon material;

a thin material of a thickness less than 2 μm thick, having a low thermal conductivity, extending between said sidewalls, and having an unsupported portion which is unsupported by any material with a higher thermal conductivity; and

a heater, formed on said unsupported portion of said low thermal conductivity material.

37. An actuator as in claim 36, wherien said thin material is less than 1 μm in thickness.

38. An actuator as in claim 37, wherein said thin material is SiN.

39. An actuator as in claim 37, wherein said membrane is formed of a material including Parylene.

40. An actuator as in claim 39, wherein said membrane is formed of a material including a first portion which is resistant against infiltration by said thermopneumatic fluid, and a second portion, which is not in contact with said themopneumatic fluid, and which includes an elastomeric sealing portion. 36-40 Dependent claims from other case.

41. A peristaltic pump, comprising:

a housing;

a plurality of heaters, located in series with one another and inside said housing spaced from one another at a predetermined spacing;

each said heater comprising a supporting sidewall foremd of a silicon material; a thin material of a thickness less than 2 μm thick, having a low thermal conductivity, extending between said sidewalls, and having an unsupported portion which is unsupported by any material with a higher thermal conductivity; and a resistive heater portion, formed on said unsupported portion of said low thermal conductivity material;

a plurality of expandable membranes, located spaced a similar spacing to a spacing between said heaters and located adjacent said heaters; and

an inlet outlet portion, having an inlet near a first of said membranes, an outlet near a last of said membranes, wherein said heaters are selectively actuated in turn to expand said membranes and to pump fluid from said first membrane via the other membranes finally to last membrane and out said outlet.

42. A pump as in claim 41, wherein said membranes each comprise:

a silicon substrate, formed to have first and second sidewalls and an open space between said first and second sidewalls;

a first layer of Parylene membrane, extending over said open space; and

a second layer of Parylene membrane, extending along said sidewalls, under said first layer of Parylene to thereby form strengthened edge portions at locations where said sidewalls meet said first layer of Parylene.

43. A pump as in claim 41, wherein said membranes each comprise a first material which is impermeable to thermopneumatic fluid and a second material which is elastomeric.

44. A pump as in claim 41,, wherein said thin material is SiN.

45. A pump as in claim 44, wherein said thin material is less than 0.5 μm thick.

46. A pump as in claim 41, wherein said membranes are formed of Parylene.

47. A pump as in claim 41, wherein said membranes are formed of Parylene and elastomer material.

48. A pump as in claim 47, wherein said elastomer material is silicone rubber.

49. A pump as in claim 41, wherein said heater includes holes therein.

50. A pump as in claim 41 further comprising a layer of silicon rubber.

51. A thermopneumatic device, comprising

a micro machined cavity, having walls formed of silicon and holding an thermopneumatically expandable liquid;

a heater, located within said cavity, and selectively actuated to selectively expand said liquid and de-actuated to contract said liquid; and

a membrane, in contact with liquid in the cavity, having a liquid impermeable film layer which has low permeability to the thermopneumatic actuation fluid, and an elastomeric substance, forming a sealing surface, said elastomeric material being isolated from the thermopneumatic actuation fluid by said liquid impermeable layer.

52. A device as in claim 51 wherein said impermeable layer is formed of Parylene.

53. A device as in claim 52 wherein said elastomeric substance is silicon rubber.

54. A device as in claim 53 wherein said heater is a resistive element on a free standing silicon nitride membrane.

55. A device as in claim 54 wherein said silicon nitride membrane is less than ½ in thickness.

56. A device as in claim 51 wherein said heater is formed with holes therein.

57. A device as in claim 51, wherein said heater is a resistive element on a substrate less than 1μm thick, and unsupported by any silicon substrate.

58. A device as in claim 51, wherein said heater is formed on a low thermal conductivity material.

59. A device as in claim 51, wherein said heater is formed of gold.

60. A device as in claim 59, wherein said heater is formed with holes therein.

61. A method of forming a composite membrane, comprising:

obtaining a silicon substrate;

opening front and rear windows on said silicon substrate which are adjacent to one another, and have a thinned silicon membrane between them;

forming a layer of thermopneumatically impermeable material on a first side of the substrate;

covering the impermeable material with an elastiomeric material on the first side of the substrate; and

removing the thin layer of silicon to leave a free standing material which is a composite of said impermeable material and said elastomeric material.

62. A method as in claim 61 further comprising forming another layer of thermopneumatically impermeable material on a second side of the layer and within the rear side window.

63. A method as in claim 61 wherein said elastomeric forming comprising filling at least a portion of the front side window with a elastomeric material.

64. A method as in claim 63 wherein said elastoeric material is silicone rubber.

65. A method as in claim 64 wherein said impermeable material is Parylene.

66. A micromachined valve seat, comprising:

a substrate formed of silicon, machined to have an inlet hole extending from a first side thereof to a second side thereof, and an outlet hole extending from first side to said second side, said first side having a first sealing surface which allows isolating said inlet from said outlet, said first sealing surface formed with a plurality of concentrically-formed grooves, which extend below a top surface of said second surface, and extend around at least one of said inlet or outlet holes.

67. A seat as in claim 66 wherein said grooves form a square concentric pattern.

68. A seat as in claim 66 further comprising an elastomeric membrane, which selectively seals and unseals one of said inlet or outlet.

69. A method of forming a micromachined valve seat, comprising:

obtaining a silicon substrate;

opening a window in a rear side of said substrate;

forming a plurality of concentric grooves in the front side of the substrate, said grooves extending down partway from the front side of the substrate but not entirely to the rear side of the substrate; and

opening a window from the rear side to the front side to form one of an inlet or outlet.

70. A micromachined valve, comprising:

a base forming a bottom portion of a cavity;

silicon side walls, forming a side portion of the cavity;

a heater formed on an unsupported substrate less than 1 μm thick, formed within said cavity, and selectively actuated to heat said cavity;

a thermopnuematic fluid, in said cavity; and

a valve portion in thermal contact with said cavity, expanding based on heating of said thermopneumatic fluid, said valve portion formed of a composite material including first

material which is impermeable to said thermopneumatic fluid and a second portion which is formed of an elastomer.

71. A valve as in claim 70 further comprising an inlet and outlet, at least one of said inlet and outlet including concentric grooves formed therearound.

72. A valve as in claim 70 further comprising an inlet and outlet, wherein said elastomer portion of said valve is in contact with one of said inlet and outlet when said fluid is heated and not in contact with other of said inlet and outlet when said fluid is not heated.

73. A valve as in claim 72 further comprising a plurality of concentric grooves around said one of said inlet and outlet.

74. A device as in claim 72 wherein said heater is formed on a thinned layer of low thermal conductivity material.

75. A device as in claim 74 wherein said thinned layer is a layer of silicon nitride less than .5 μm thick.

76. A device as in claim 70 wherein said elastomeric material is silicon rubber.

77. A device as in claim 70 wherein said impermeable material is Parylene.

78. A device as in claim 75 wherein said elastomeric material is silicon rubber and said impermeable material is Parylene.

79. A device as in claim 78 wherein said heater includes a plurality of holes therein, allowing pressure on one side of the heater to equalize with pressure on the other side of the heater.

80. A device as in claim 78 wherein said heater is substantially in a central portion of said cavity.

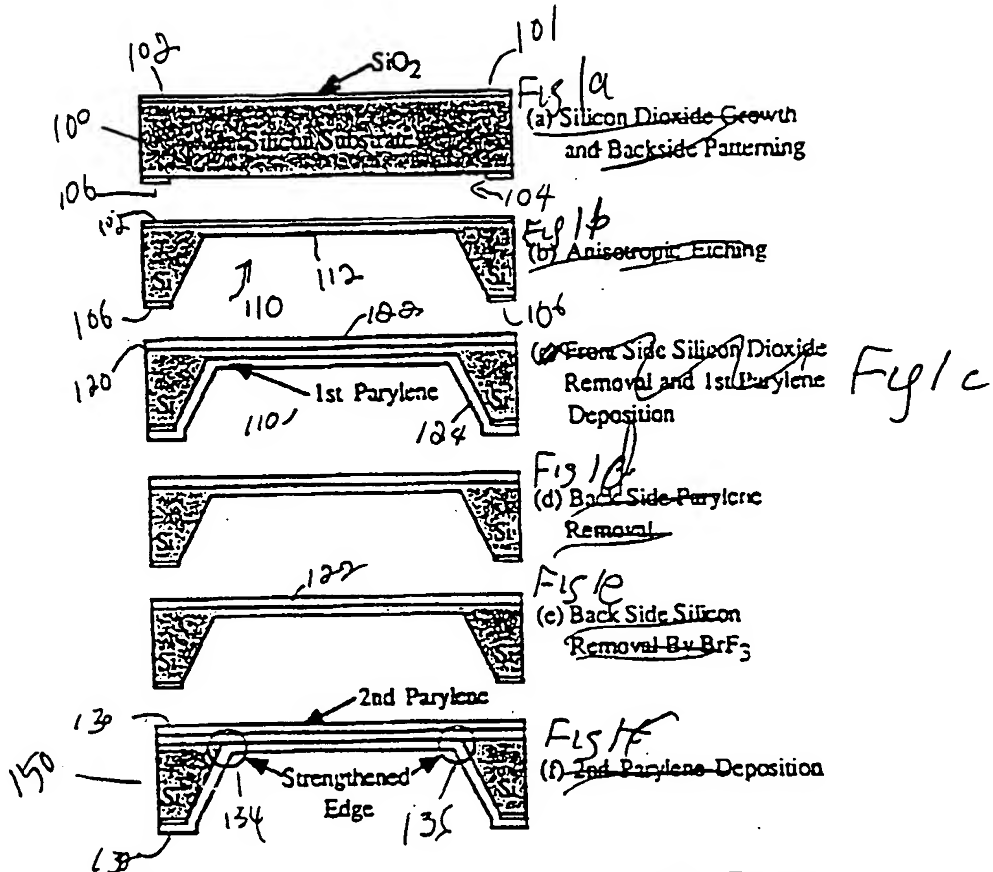


Figure 1. Parylene Membrane Fabrication Process

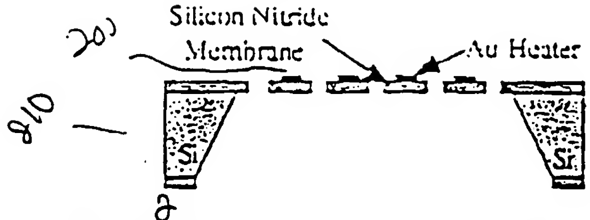


Figure 2. Cross-sectional view of the Heater

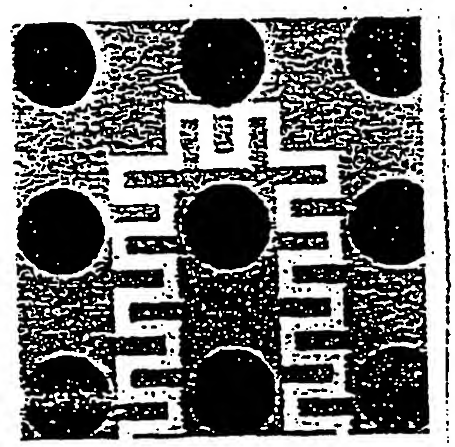


Figure 3. Picture of a Fabricated Heater

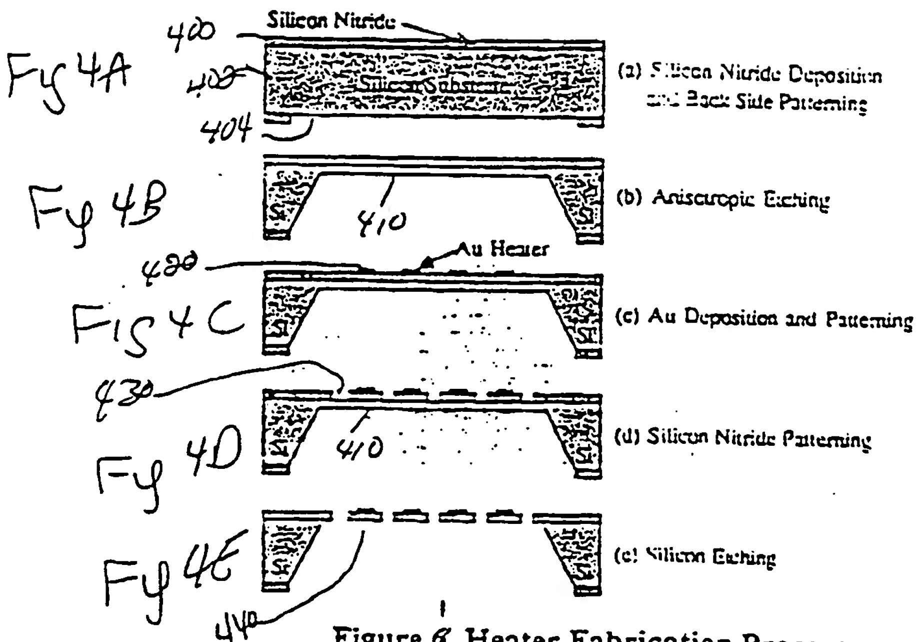


Figure ~~6~~ 4. Heater Fabrication Process

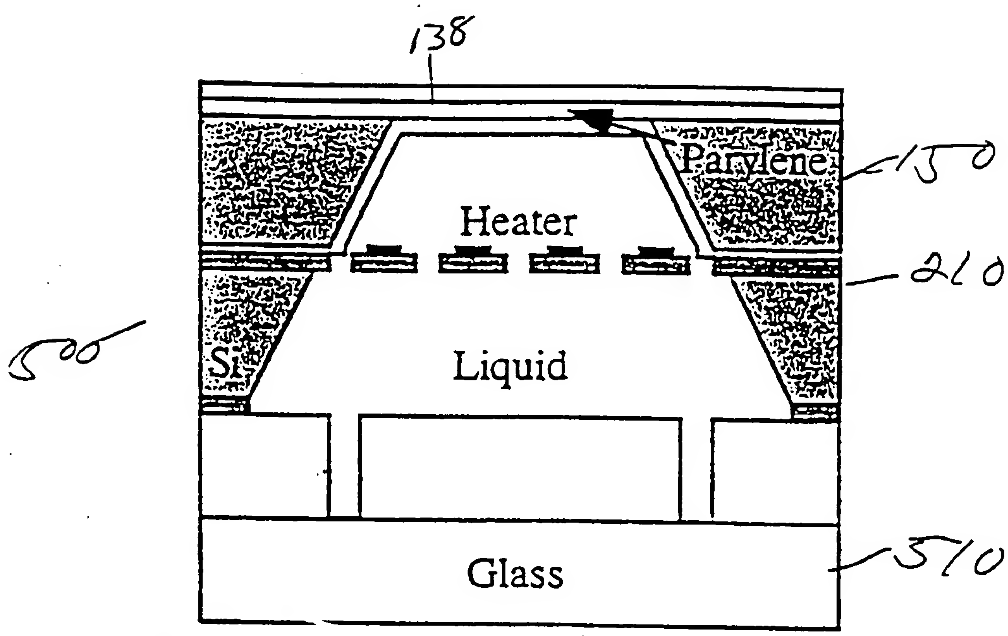


Figure 5. Cross-sectioanl View of the Thermopneumatic Actuator

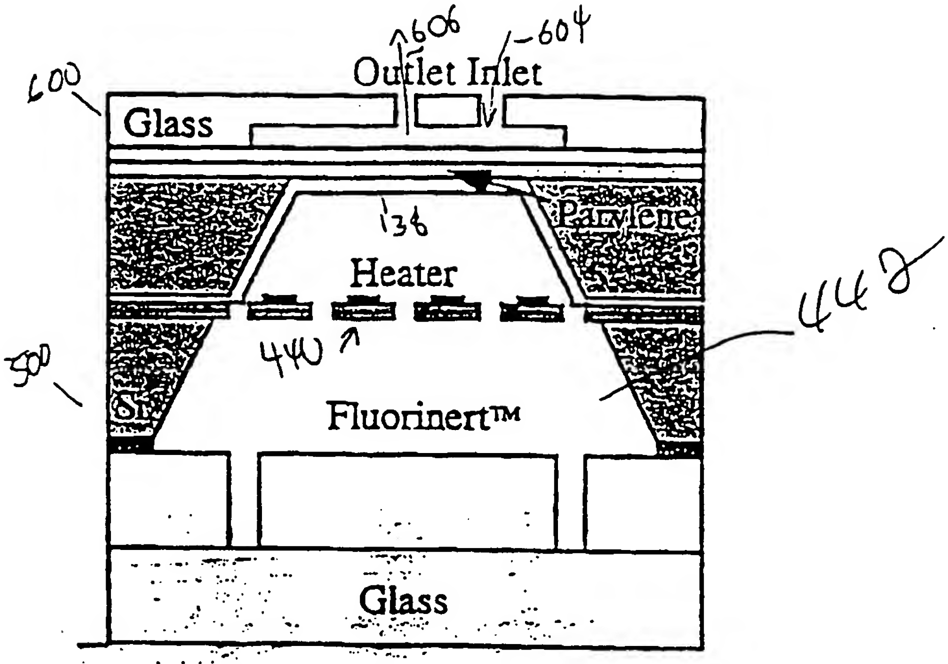


Figure 6. Cross-sectional View of the Normally Open Valve

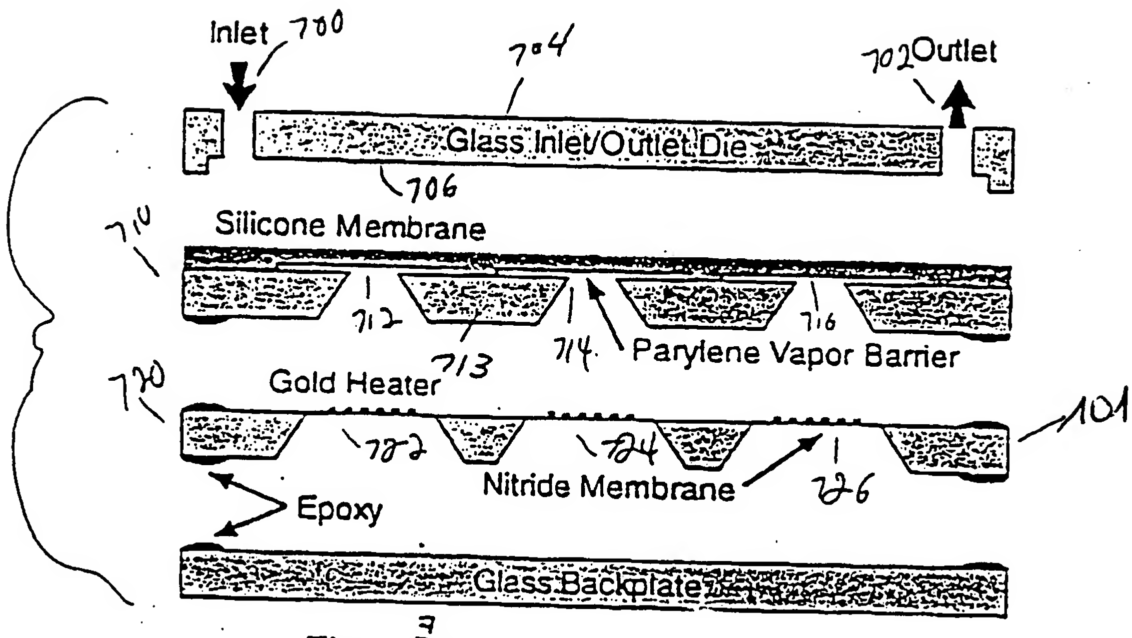
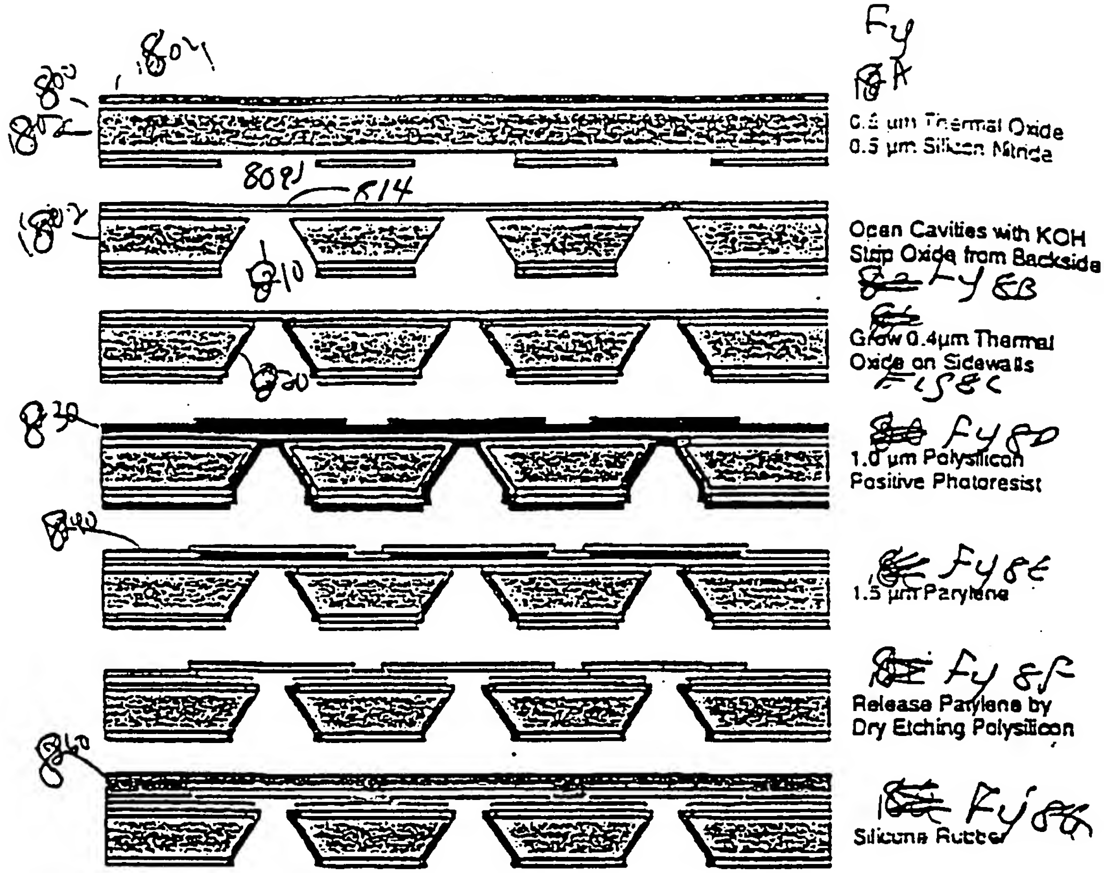
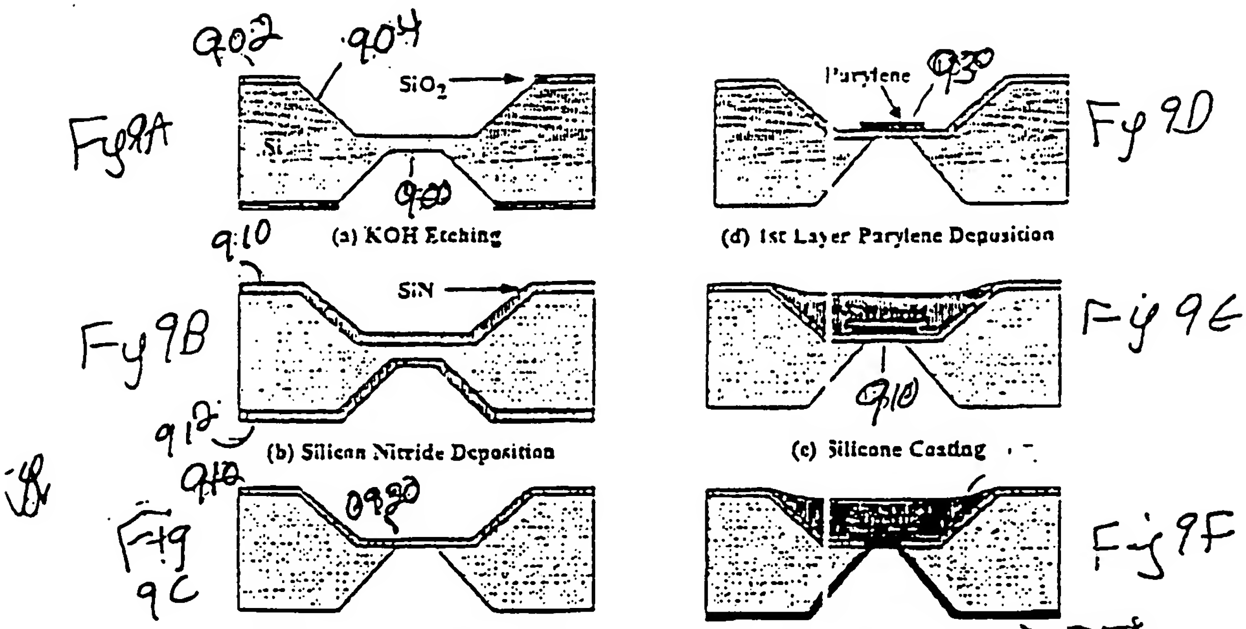


Figure 7. Peristaltic Pump Components


0.5 µm Thermal Oxide
0.5 µm Silicon Nitride
Open Cavities with KOH
Strip Oxide from Backside
Grow 0.4µm Thermal
Oxide on Sidewalls
1.0 µm Polysilicon
Positive Photoresist
1.5 µm Parylene
Release Parylene by
Dry Etching Polysilicon
Silicone Rubber



(a) KOH Etching

(b) Silicon Nitride Deposition

(c) SiN Etching and Silicon Etching

(d) 1st Layer Parylene Deposition

(e) Silicone Coating

(f) 2nd Layer Parylene Deposition

Fig 10

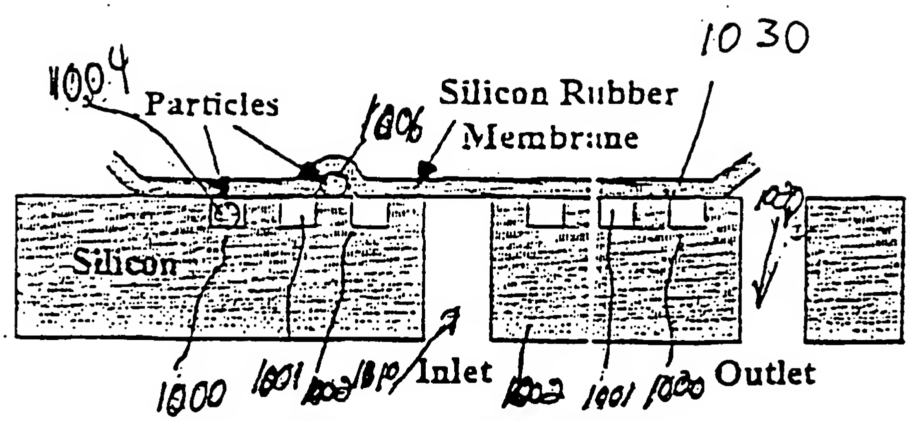


Figure 5. A Novel Valve Seat

Fig 11

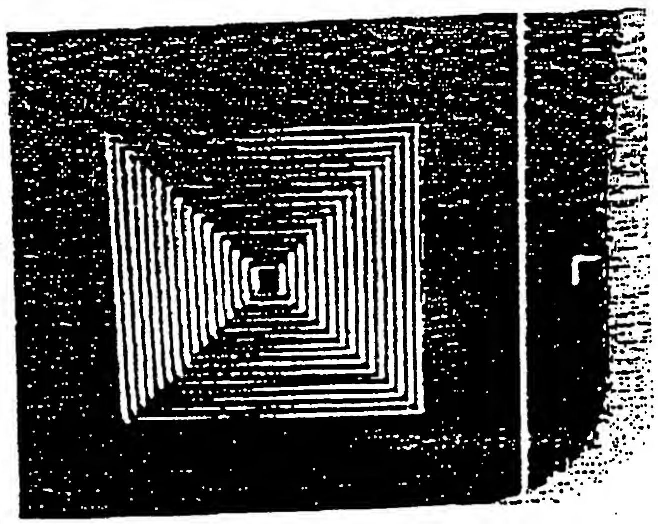
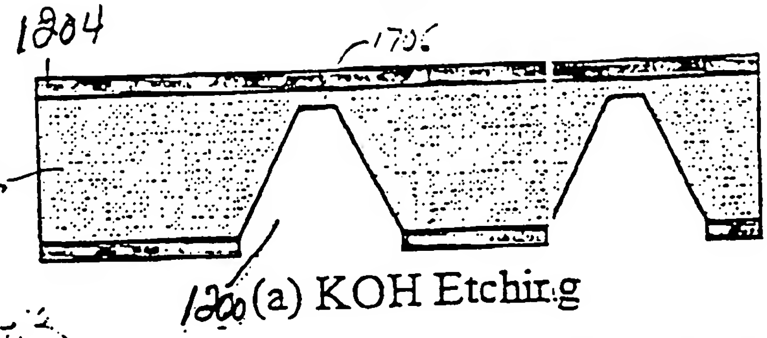


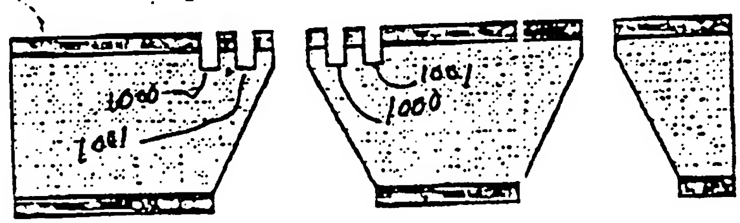
Figure 7. A Fabricated Valve Seat

Fig 12A



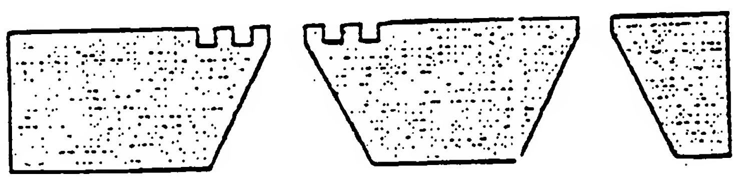
(a) KOH Etching

Fig 12B

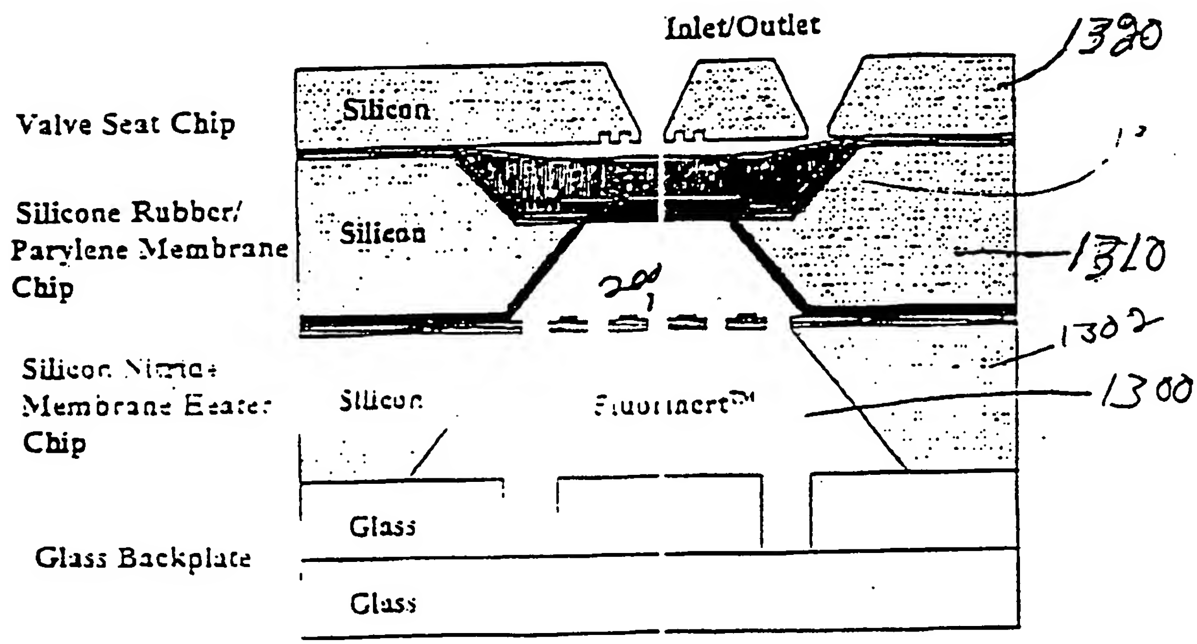


(b) Reactive Ion Etching

Fig 12C



(c) Silicon Dioxide Removal


Inlet/Outlet
1320
Valve Seat Chip
Silicon
Silicone Rubber/
Parylene Membrane
Chip
Silicon
1310
200
1302
Silicon Nitride
Membrane Heater
Chip
Silicon
Fluorinert™
1300
Glass
Glass Backplate
Glass

Fig

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/24072

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :F16K 27/00
US CL : 251/11, 368, 359; 60/530
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 251/11, 368, 359, 61.1; 60/530

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,824,073 A (ZDEBLICK) 25 April 1989, col. 6, line 33 thru col. 7, line 6.	1, 6, 15, 22, 35, 41, 51 and 70
A	US 5,177,579 A (JERMAN) 05 January 1993, col. 9, lines 23-30.	2, 4 and 61
A	US 5,175,358 A (BONNE et al) 05 January 1993, col. 10, lines 3-20.	66 and 69

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 FEBRUARY 1999	12 MAR 1999

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	KEVIN LEE Diane Smith for
Facsimile No. (703) 305-3230	Telephone No. (703) 308-1025